

B Hadron Lifetime Results from CDF

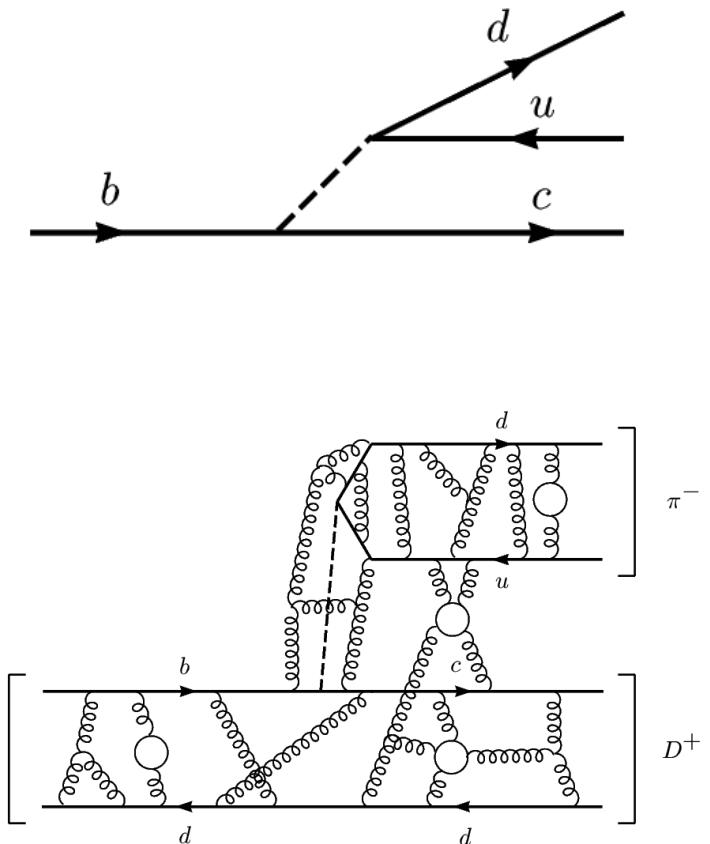
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on behalf of the CDF collaboration

14 December 2006

- Motivation
- CDF Overview
- B^0 and B^+ Lifetime Results
- Λ_b^0 Lifetime Results
- B_s^0 Lifetime Results

Why Measure Lifetimes?

- The width (Γ) is inversely proportional to the lifetime (τ) of a particle. Sensitive to: strong, electro-magnetic, and weak forces.
- Weak hadronic decays depend on fundamental parameters of the Standard Model; *i.e.* CKM Matrix elements and quark masses.
- The “Real World” is not characterized by simple, free quark decays.
Complicates theoretical interpretation of experimental observations.
- Lifetimes of weakly decaying hadrons of the same heavy flavor help to quantify the connection between the “Real World” and Theory.
Study the interplay between the strong and weak forces
Helps us understand non-perturbative effects of QCD



Theoretical Predictions

Qualitative B lifetime hierarchy: $\tau(B^+) \geq \tau(B^0) \sim \tau(B_s^0) > \tau(\Lambda_b^0) >> \tau(B_c)$

Heavy Quark Expansion (HQE) predicts values for weakly decaying hadrons

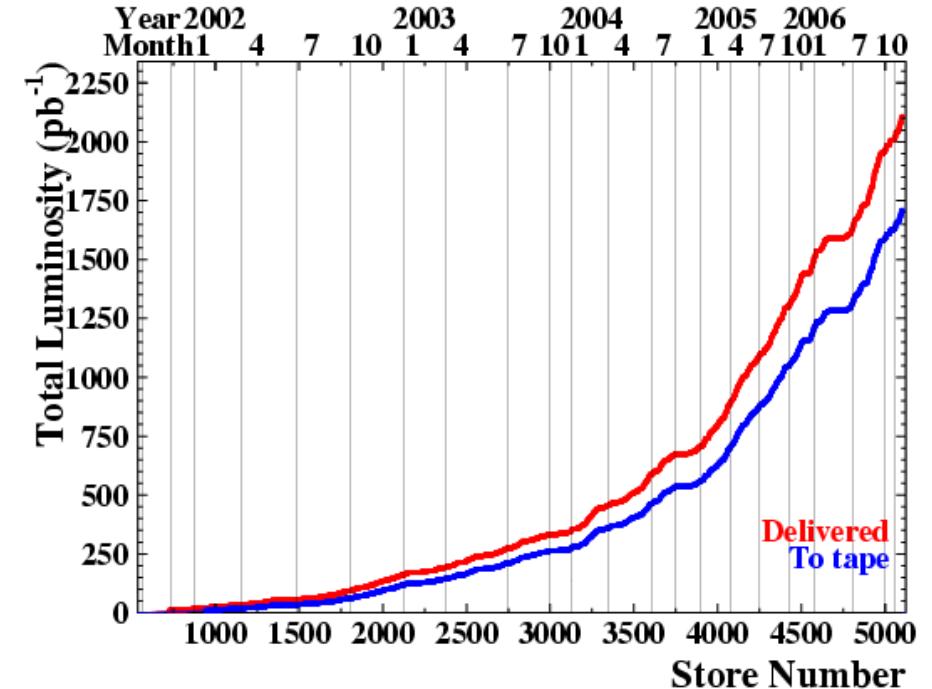
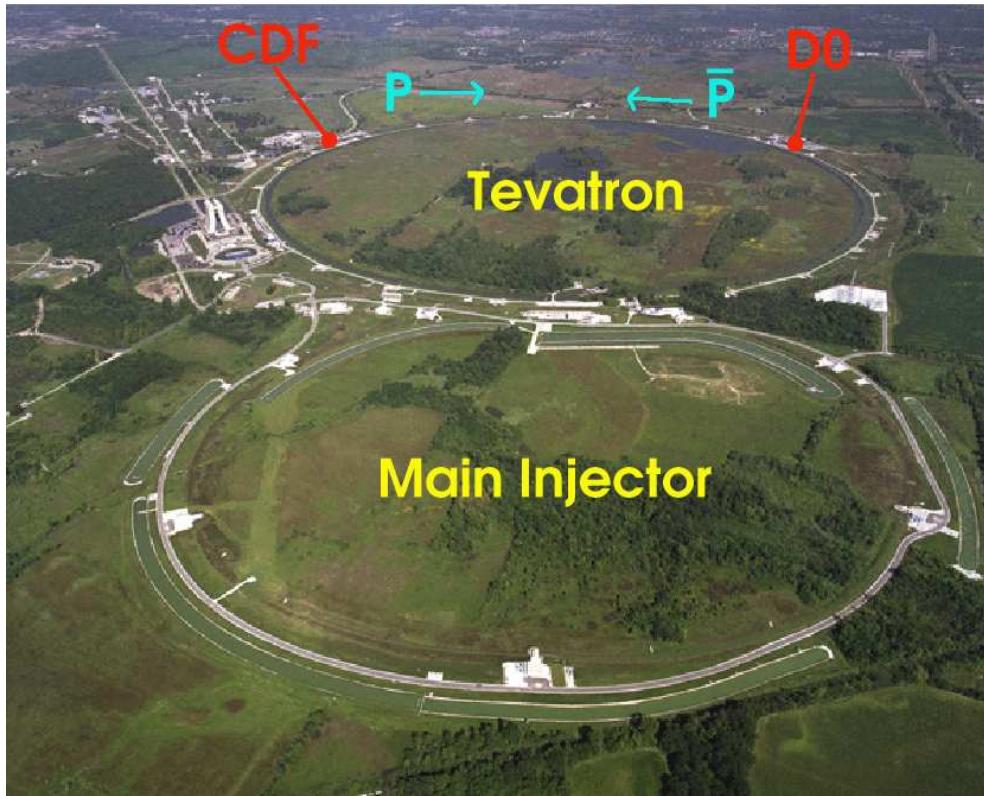
$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \cdot \left[A_0 + A_2 \left(\frac{\Lambda_{QCD}}{m_b} \right)^2 + A_3 \left(\frac{\Lambda_{QCD}}{m_b} \right)^3 + \dots \right]$$

Theoretical lifetime predictions:

- $\tau(B^+)/\tau(B^0) = 1.06 \pm 0.02$
- $\tau(B_s^0)/\tau(B^0) = 1.00 \pm 0.01$
- $\tau(\Lambda_b^0)/\tau(B^0) = 0.88 \pm 0.05$

C. Tarantino *et al* hep-ph/0310241

The Tevatron at Fermilab

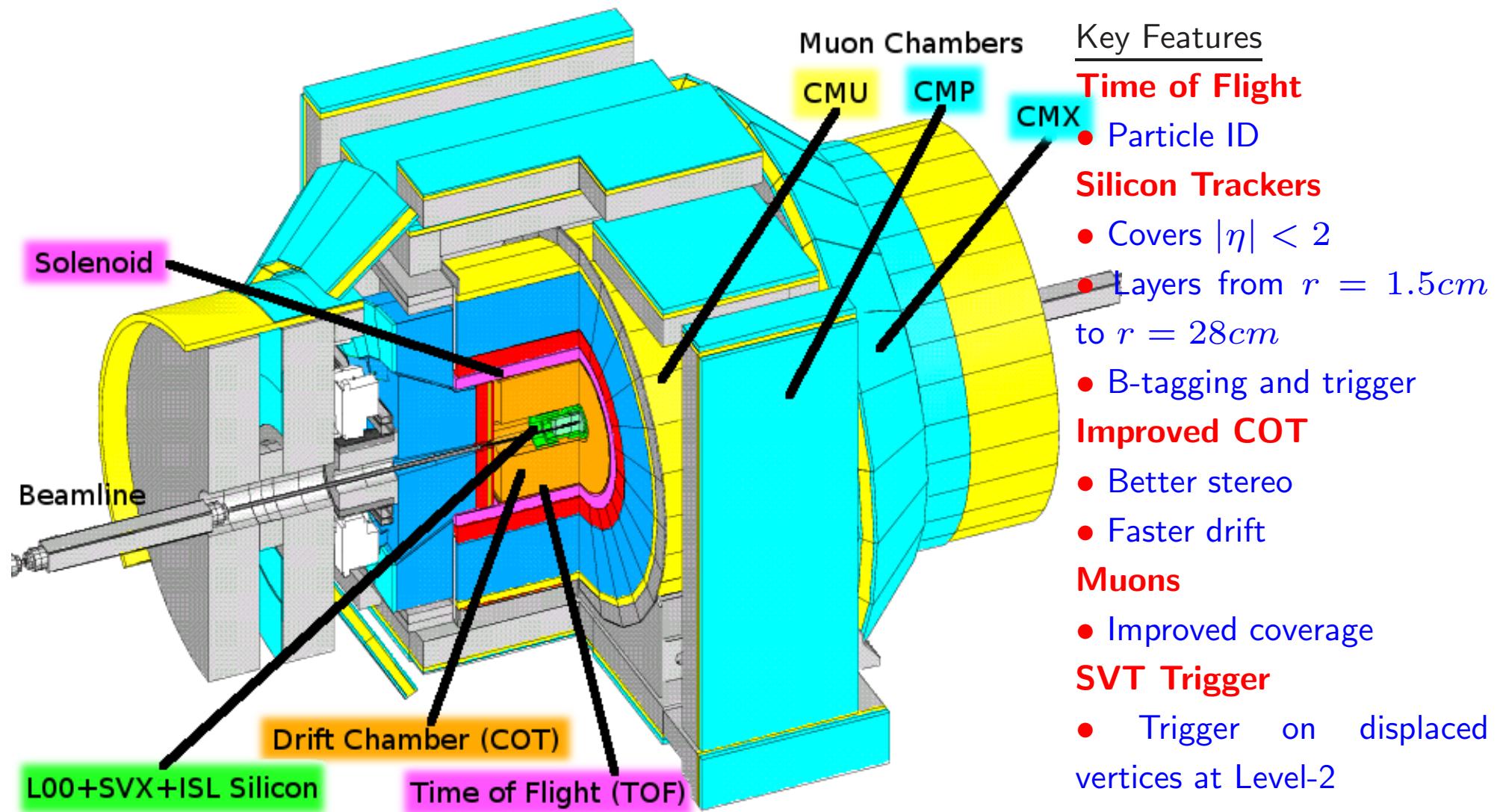


Tevatron is the highest energy particle collider.

- $\sqrt{s} = 1.96 \text{ TeV}$
- $\int L dt > 2 fb^{-1}$ delivered ($1.6 fb^{-1}$ on tape at CDF)
- Record initial luminosity: $237 e30$
- $4 - 8 fb^{-1}$ expected at end of 2009

All B flavors are produced at the Tevatron: B^+ , B^0 , B_s^0 , Λ_b^0 , B_c , etc..

Collider Detector at Fermilab (CDF) Run II

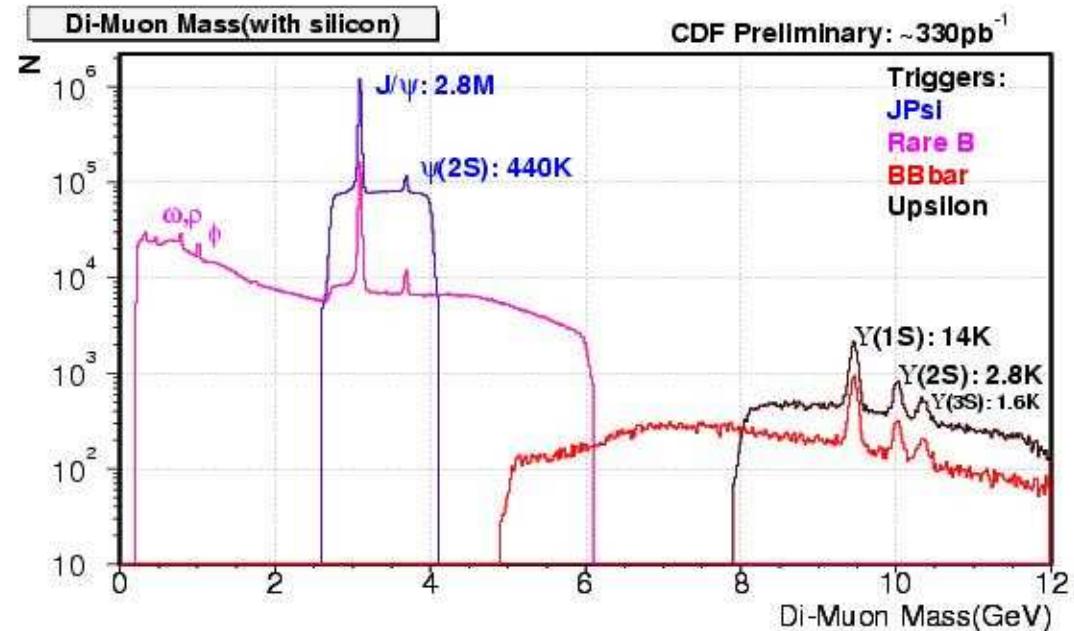


B Triggers: Di-Muon (J/ψ) Trigger

$\sigma_{b\bar{b}}$ is very large, but cross-section of soft QCD is ~ 1000 x larger
 \Rightarrow b-physics program lives and dies by the trigger!

Important Trigger Paths

- Di-Lepton Triggers (J/ψ)
- Lepton + Displaced Track
- Two Displaced Tracks (TTT)

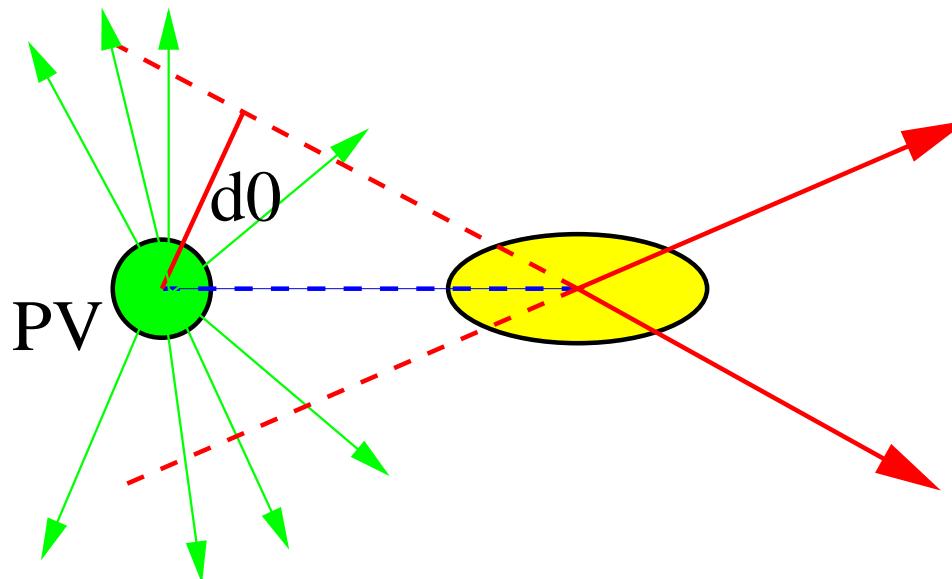


Di-Muon Trigger Requirements

- $Q(\mu)Q(\mu') = -1$
- $p_T(\mu) > 1.5 \text{ GeV}/c$
- $2.7 < m(\mu\mu') < 4 \text{ GeV}/c^2$

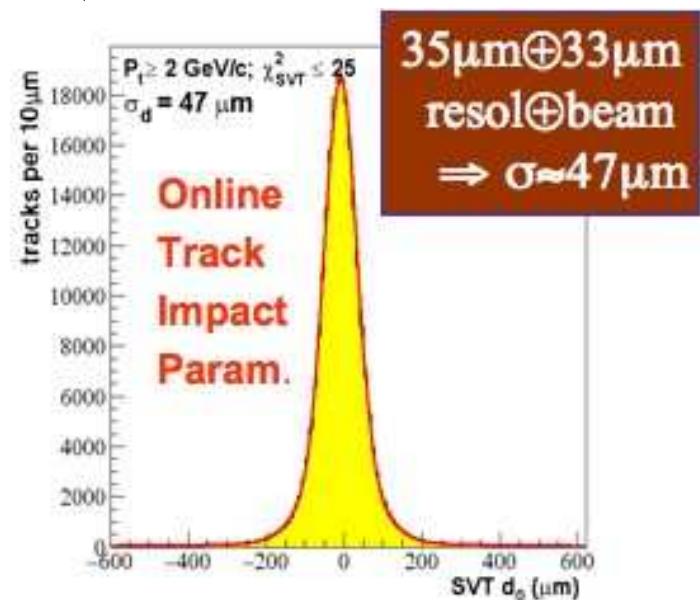
B Triggers: Displaced Track Trigger

CDF also triggers on Two Displaced Tracks (TTT)



- ⇒ Silicon Vertex Trigger (SVT): part of trigger system that finds displaced tracks and triggers on heavy flavor
- $120\mu m \leq d0(trk) \leq 1mm$
 - $p_T(trk) > 2\text{GeV}/c$
 - $\Sigma p_T > 5.5\text{GeV}/c$
 - $2^\circ < \Delta\phi < 90^\circ$

Excellent trigger for selecting heavy flavor
Lifetime measurement is biased by trigger requirement
Trigger bias must be accounted for properly!

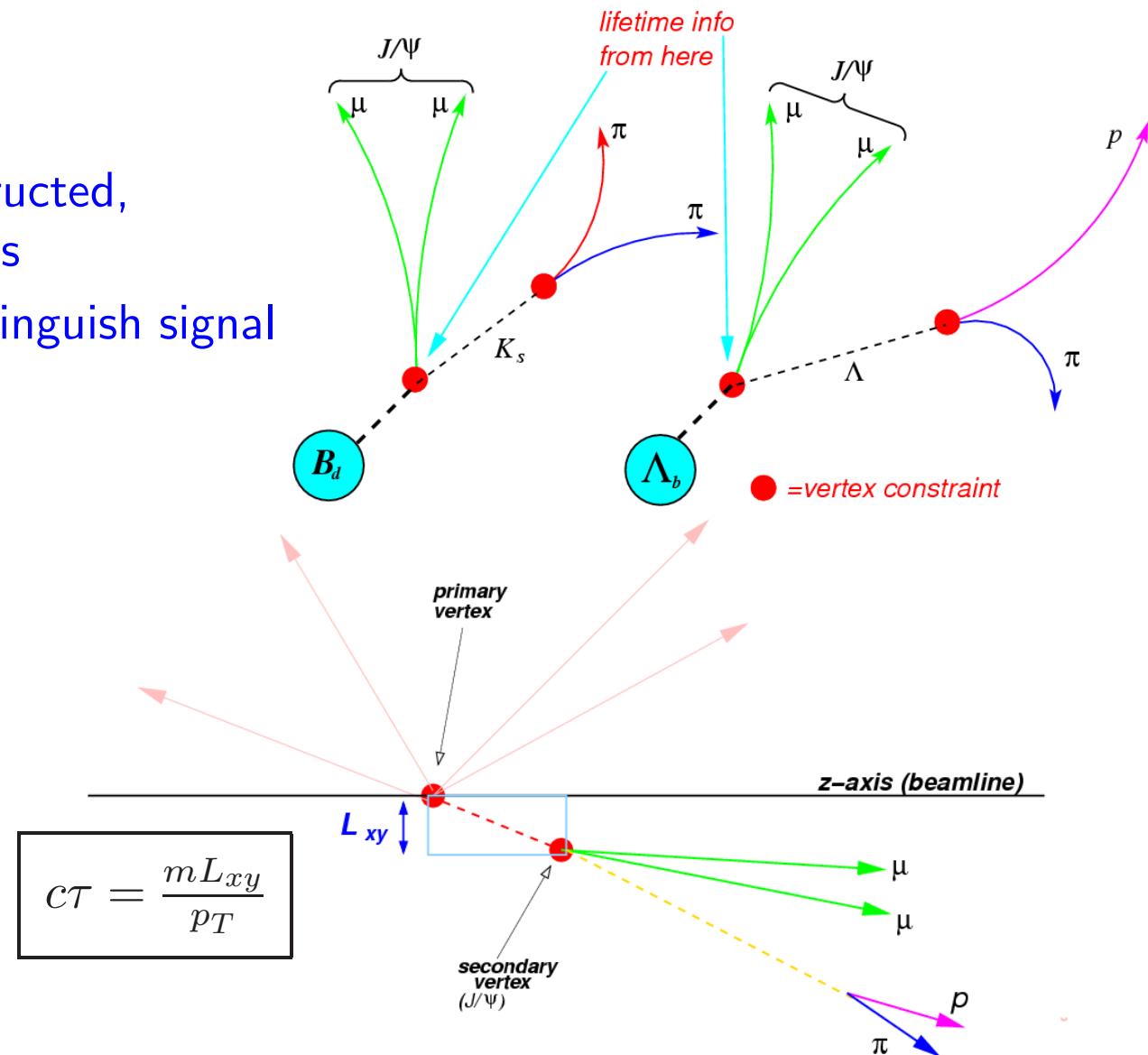


General J/ψ Analysis Strategy

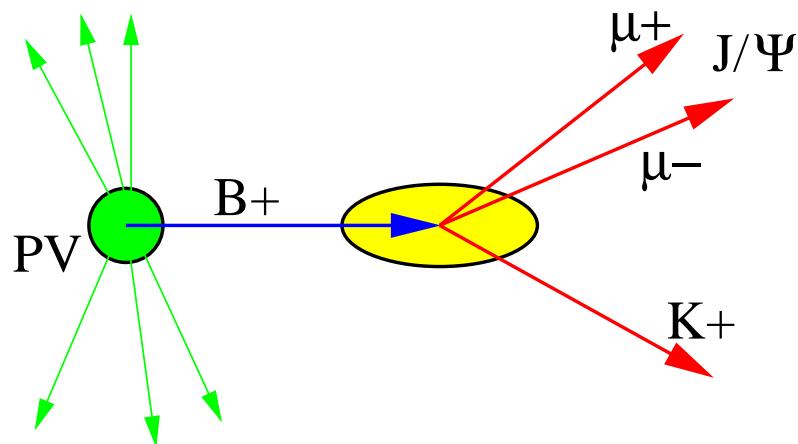
- Use di-muon trigger
- Measure τ in fully-reconstructed, $B \rightarrow J/\psi X$ decay channels
- Provides mass peak to distinguish signal from background
- No missing momentum

The same technique used on the following modes;

- $B^+ \rightarrow J/\psi K^+$
- $B^0 \rightarrow J/\psi K^{0*}$
- $B^0 \rightarrow J/\psi K_s^0$
- $\Lambda_b^0 \rightarrow J/\psi \Lambda$
- $B_s^0 \rightarrow J/\psi \phi$



Measuring the Lifetime (I)

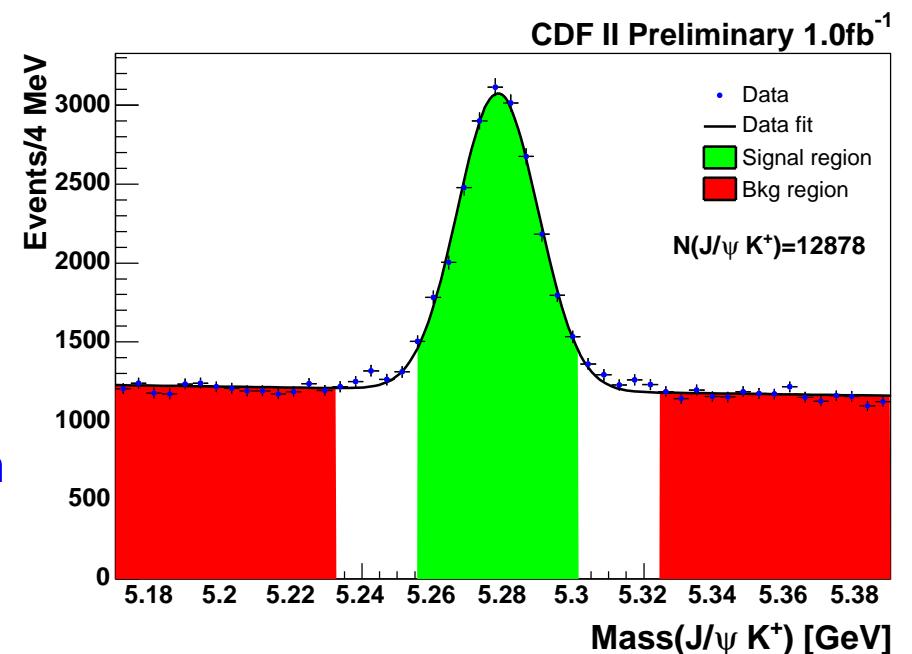


Track(s) are vertexed with J/ψ to form a “B” candidate

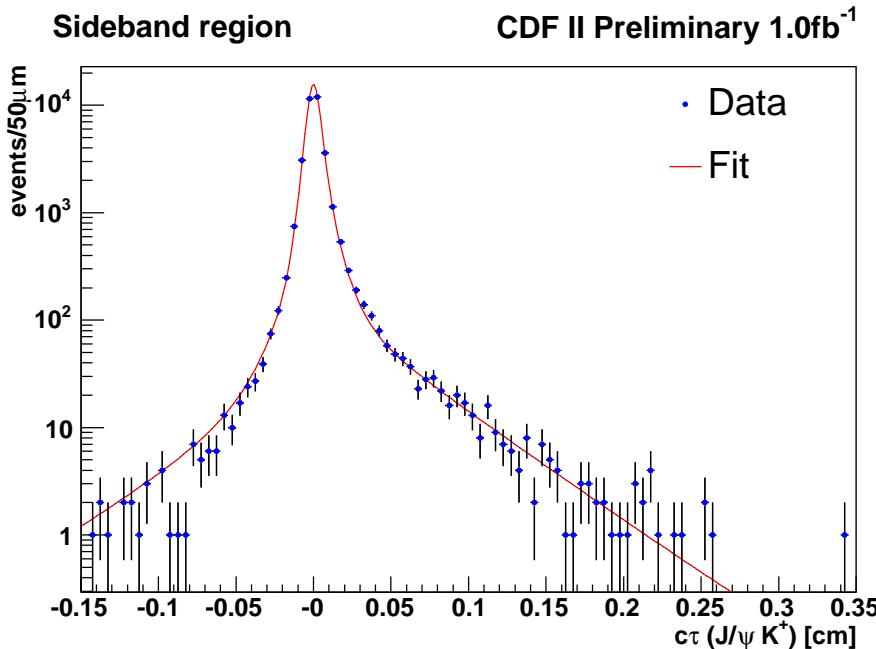
Simplest case: $B \rightarrow J/\psi K^+$

$$N(J/\psi K^+) \sim 12,900$$

Define Sideband and Signal regions
Background templates derived from sidebands



Measuring the Lifetime (II)



Different $\sigma_{c\tau}$ distributions used for signal and background.

$$S(\sigma_{c\tau}) = \sum_{i=1}^3 A_i (\sigma_{c\tau})^{a_i} e^{-\sigma_{c\tau}/b_i}$$

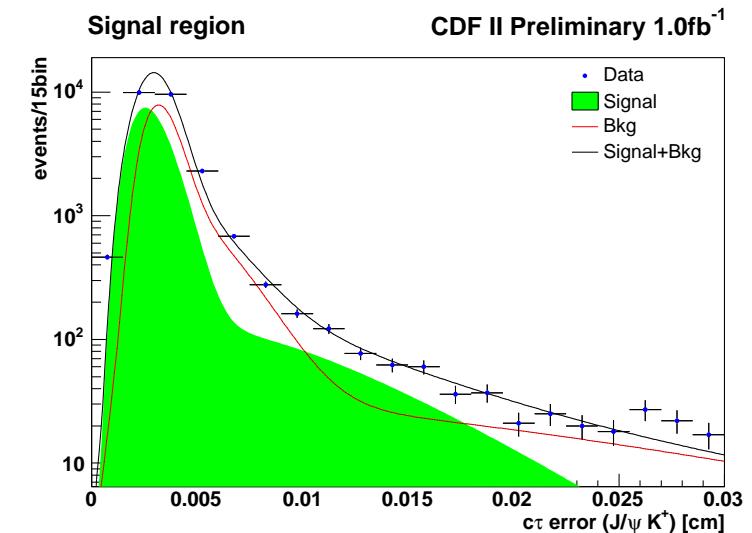
$$P_t(ct, \sigma_{c\tau}) = T(ct | \sigma_{c\tau}) \cdot S(\sigma_{c\tau})$$

Proper time distribution described by;

$$T(ct; \bar{\tau} | \sigma_{c\tau}) = \int \frac{1}{\bar{\tau}} e^{-ct/c\bar{\tau}} \otimes \text{Gauss}(ct) d(ct)$$

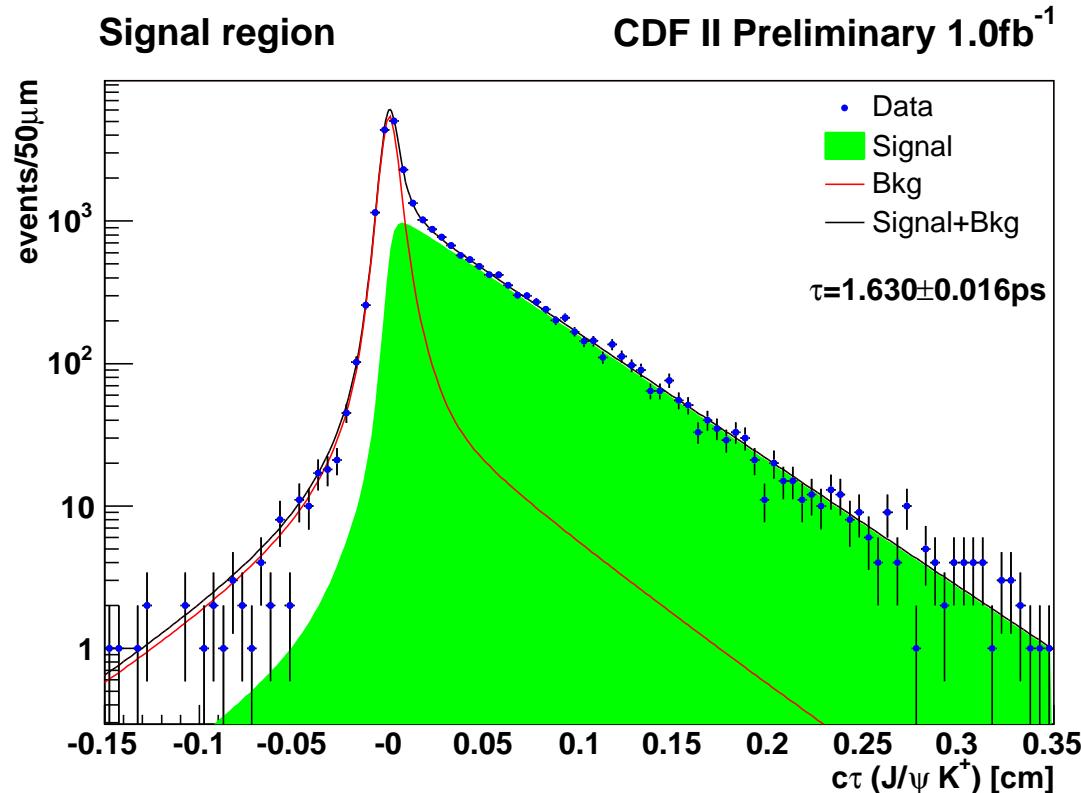
Signal: $\bar{\tau} = \tau_B$

Background: $\bar{\tau}$ describes negative, prompt, and positive lifetimes.



B^+ Lifetime: $B^+ \rightarrow J/\psi K^+$

$$\mathcal{L}(m, c\tau, \sigma_{c\tau}, \sigma_m) = f_s \cdot P_m^s(m, \sigma_m) \cdot P_t^s(c\tau, \sigma_{c\tau}) + (1 - f_s) \cdot P_m^b(m, \sigma_m) \cdot P_t^b(c\tau, \sigma_{c\tau})$$



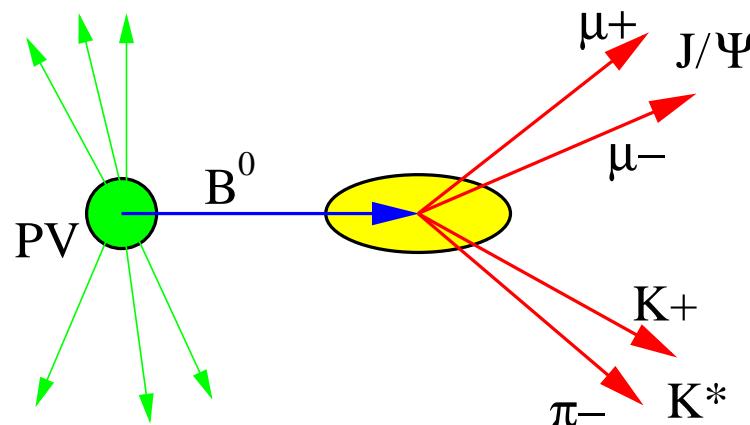
$$c\tau(B^+) = 488.6 \pm 4.8(\text{stat}) \pm 3.2(\text{syst}) \mu\text{m}$$

$$\tau(B^+) = 1.630 \pm 0.016(\text{stat}) \pm 0.011(\text{syst}) \text{ps}$$

Unbinned maximum log-likelihood fit used to fit lifetime
Simultaneous fit of mass (m), lifetime ($c\tau$), and lifetime error ($\sigma_{c\tau}$)

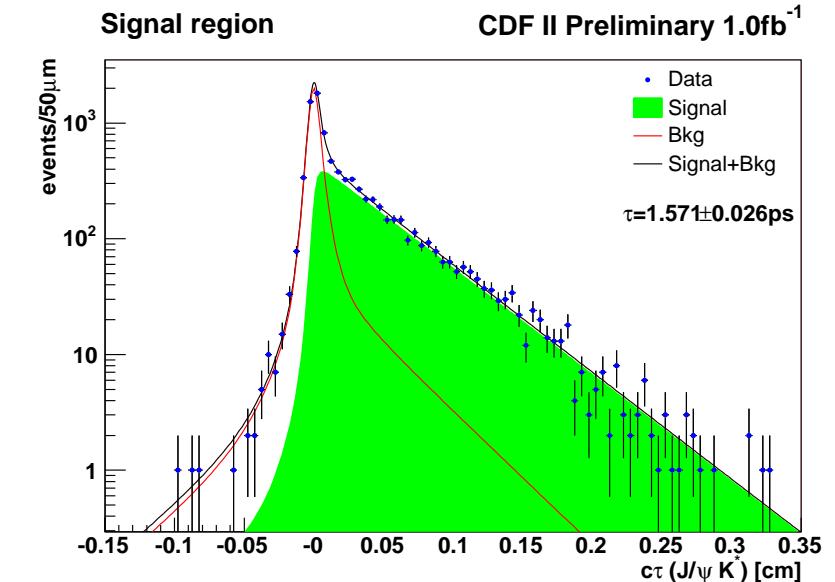
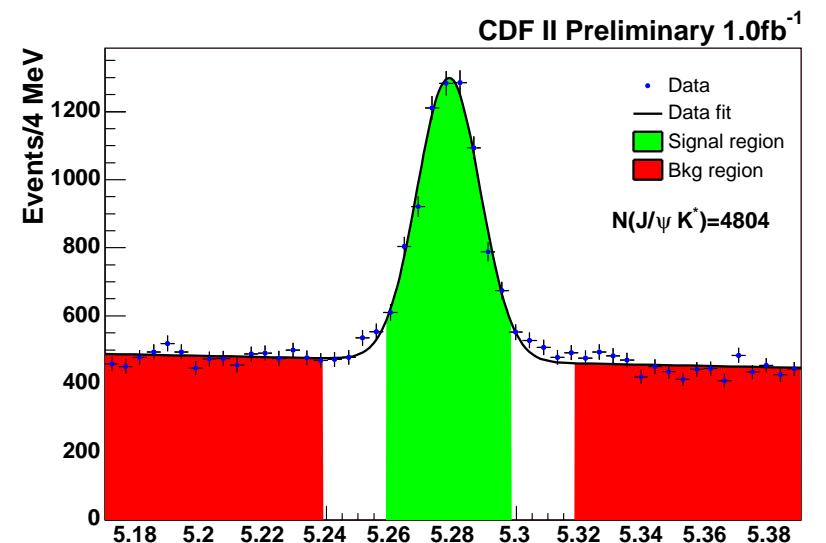
The same method is applied to other modes

B^0 Lifetime: $B^0 \rightarrow J/\psi K^{*0}$

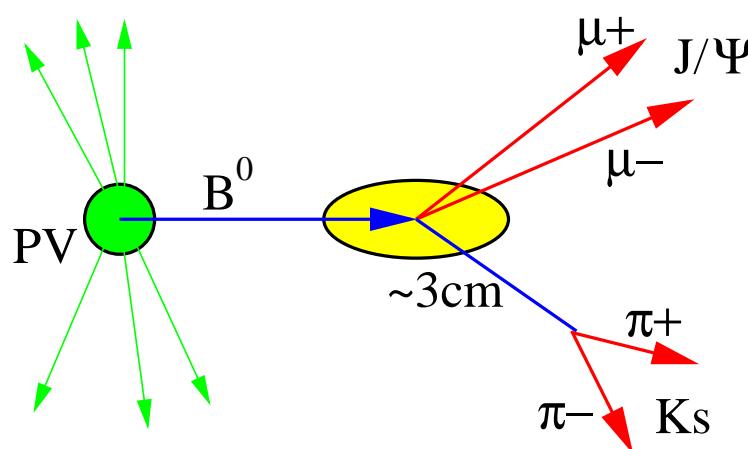


$$N(J/\psi K^{*0}) \sim 4800$$

$c\tau(B^0) = 471.3 \pm 7.6(stat) \pm 3.7(syst)\mu m$
 $\tau(B^0) = 1.571 \pm 0.026(stat) \pm 0.013(syst)ps$



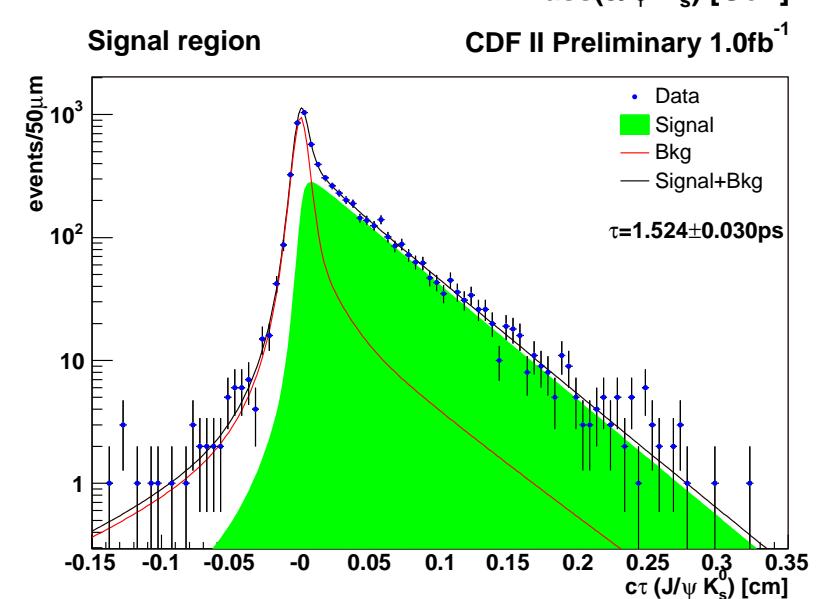
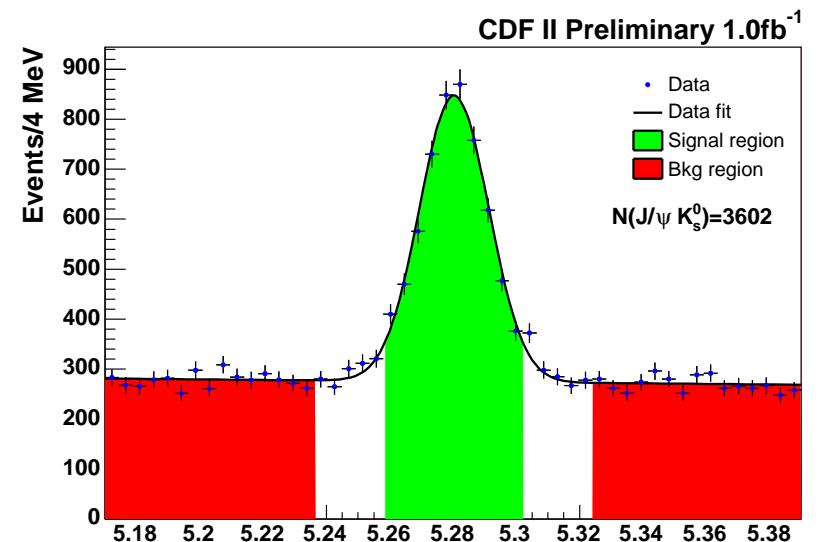
B^0 Lifetime: $B^0 \rightarrow J/\psi K_s^0$



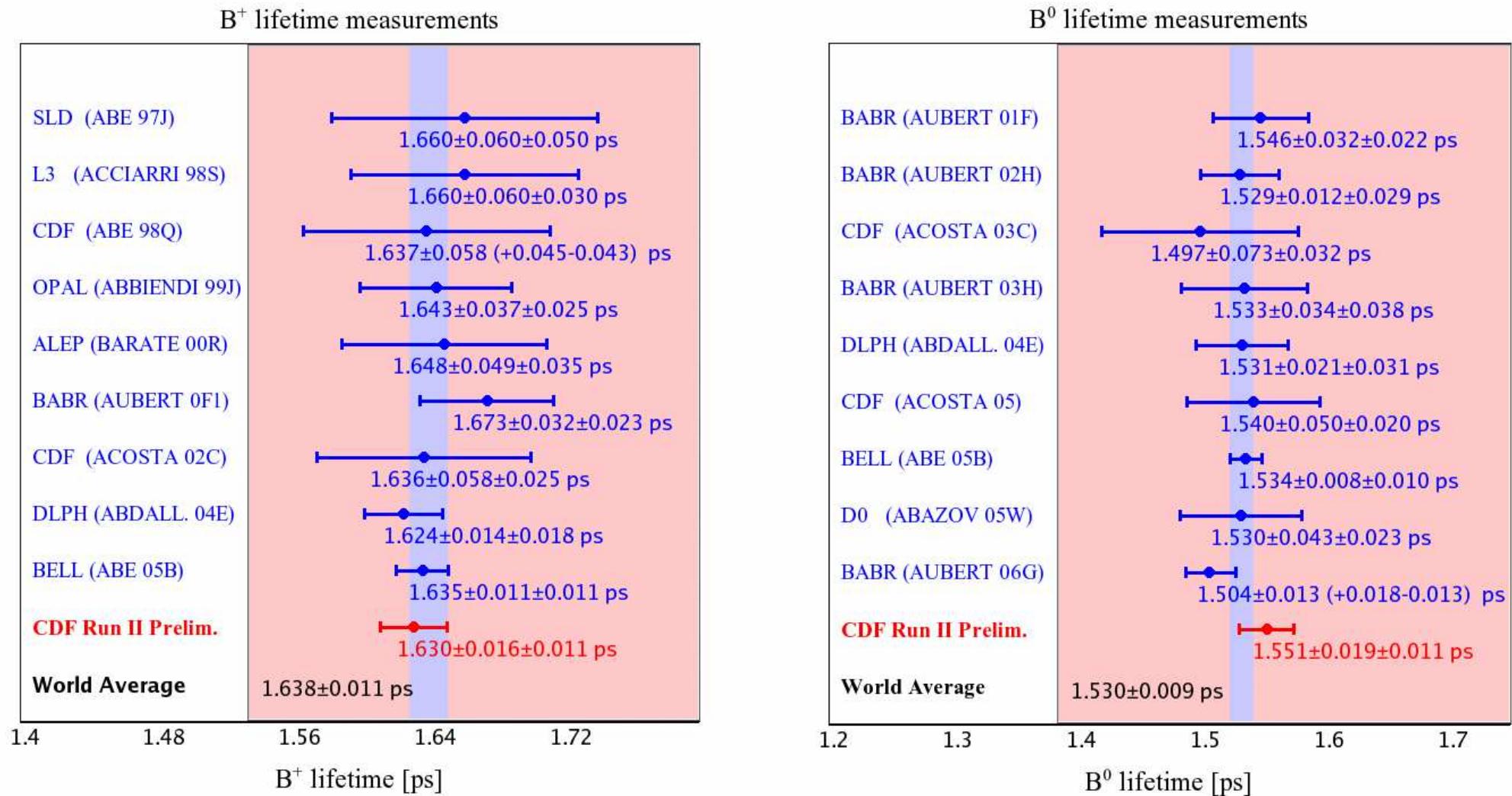
- Veto Λ_b^0 ($p\pi$ candidates)
- K_s^0 pointing used to constrain B^0 vertex

$$N(J/\psi K^{*0}) \sim 3600$$

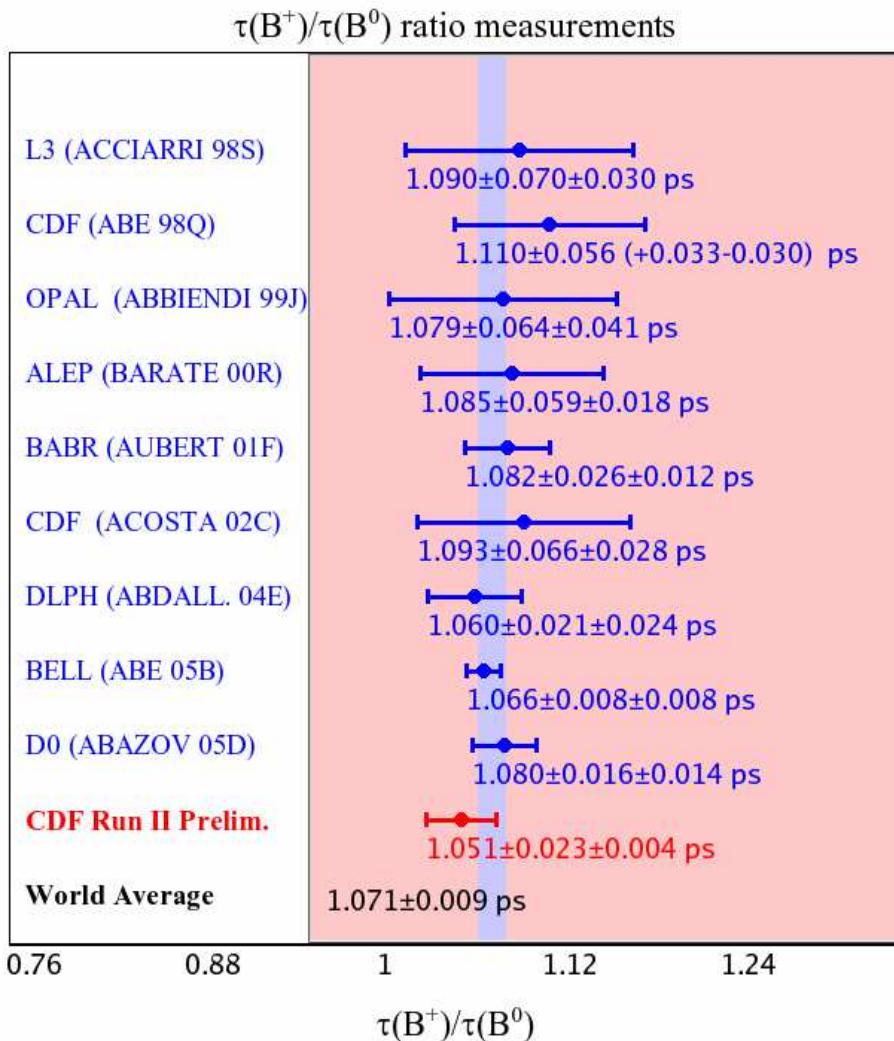
$c\tau(B^0) = 457.1 \pm 8.8(stat) \pm 3.2(syst)\mu m$
 $\tau(B^0) = 1.524 \pm 0.030(stat) \pm 0.011(syst)ps$



Summary of B^+ and B^0 Lifetimes



B^+, B^0 Lifetime ratio



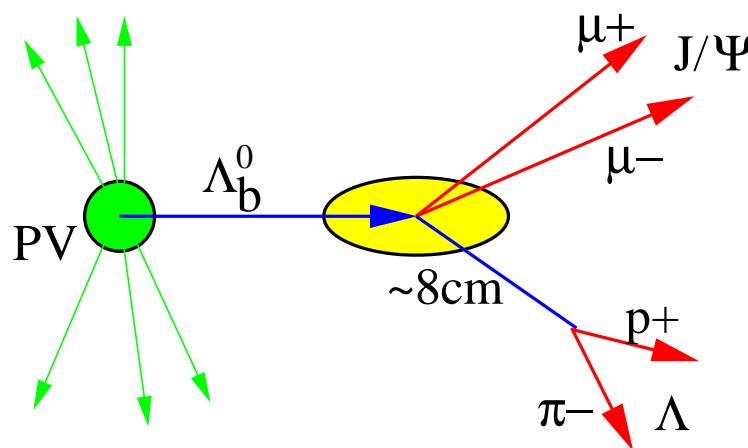
$$\frac{\tau(B^+)}{\tau(B^0)} = 1.051 \pm 0.023(stat) \pm 0.004(syst)$$

Very good agreement with world average
Very good agreement with prediction

$$\tau(B^+)/\tau(B^0) = 1.06 \pm 0.02$$

results from B^+ and B^0 help to build confidence in the method

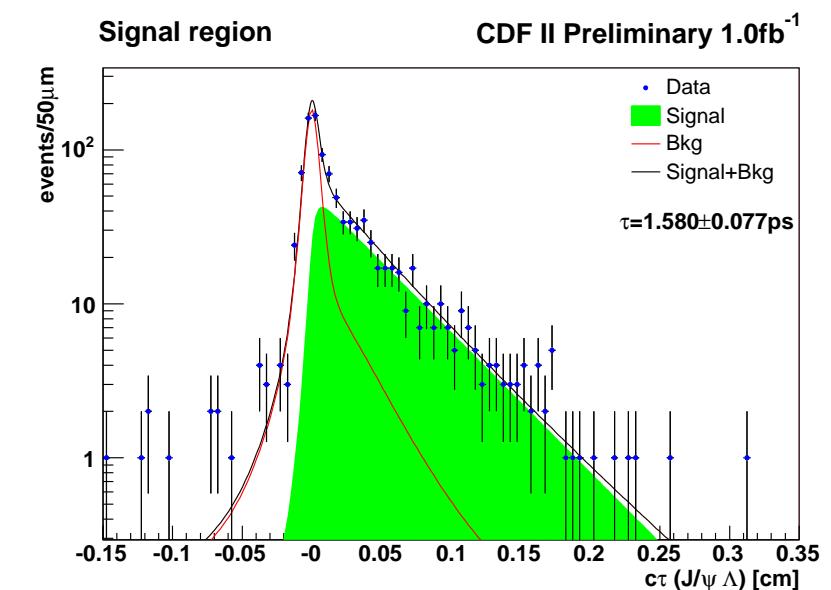
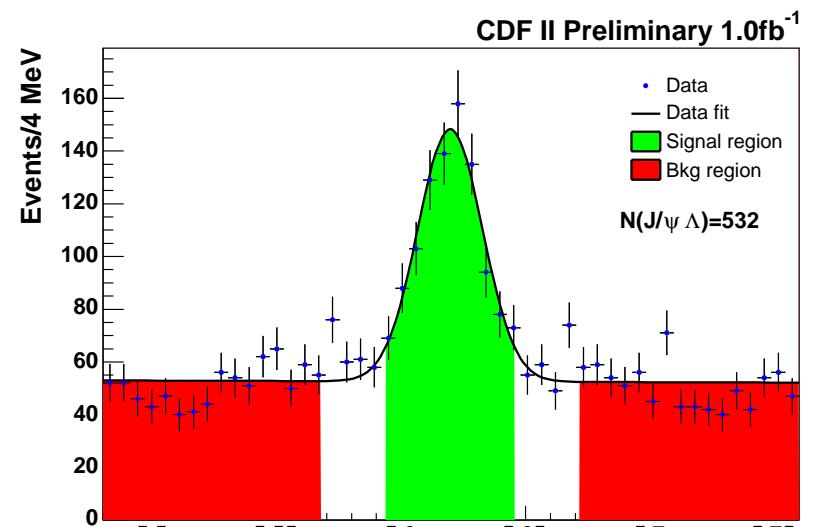
$\Lambda_b^0 \rightarrow J/\psi \Lambda$ Lifetime



- Veto K_s^0 ($\pi \pi$ candidates)
- Λ pointing used to constrain Λ_b^0 vertex

$$N(J/\psi \Lambda) = 532$$

$c\tau(\Lambda_b^0) = 473.8 \pm 23.1(\text{stat}) \pm 3.5(\text{syst}) \mu\text{m}$
 $\tau(\Lambda_b^0) = 1.580 \pm 0.077(\text{stat}) \pm 0.012(\text{syst}) \text{ps}$



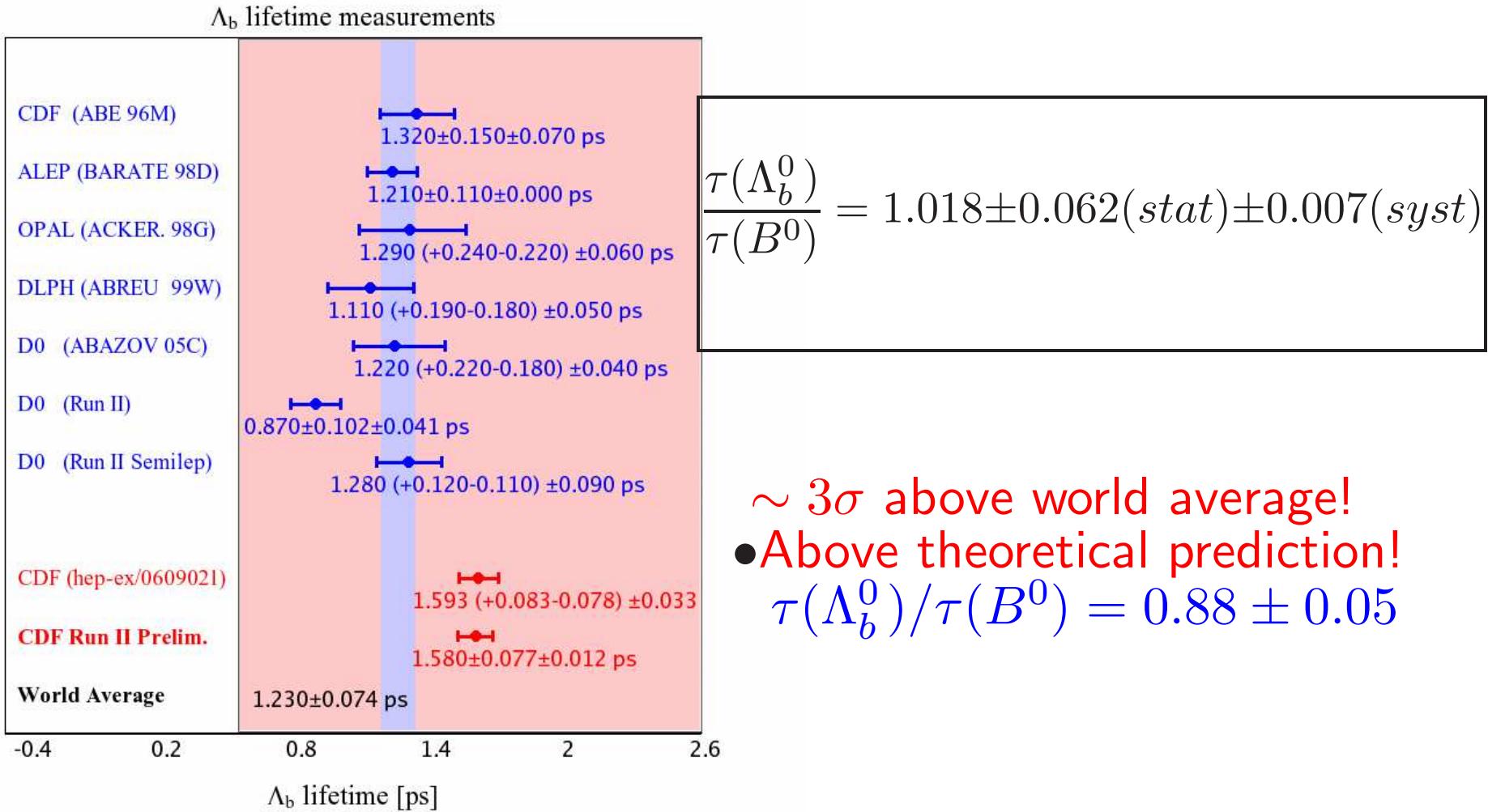
$\Lambda_b^0 \rightarrow J/\psi \Lambda$ Systematics

Same sources of systematic error in Λ_b^0 as in B^+ and B^0 modes

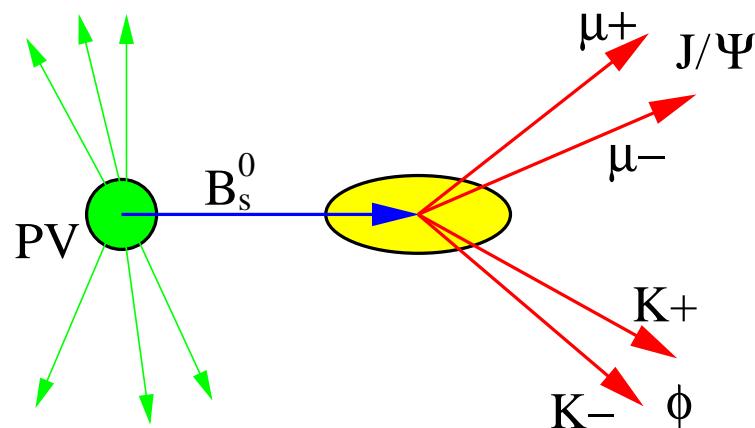
Source	Error (μm)
Alignment	± 2.0
Background Model	0.8
Background Mass Model	-2.1
Signal Mass Model	-0.1
PDL Error	+0.3
Resolution universal	-1.1
Resolution modeling	<i>negligible</i>
Total	± 3.5

Detector alignment and background mass model dominate systematic errors

Summary of Λ_b^0 Lifetime Measurements



$B_s^0 \rightarrow J/\psi \phi$ Lifetime

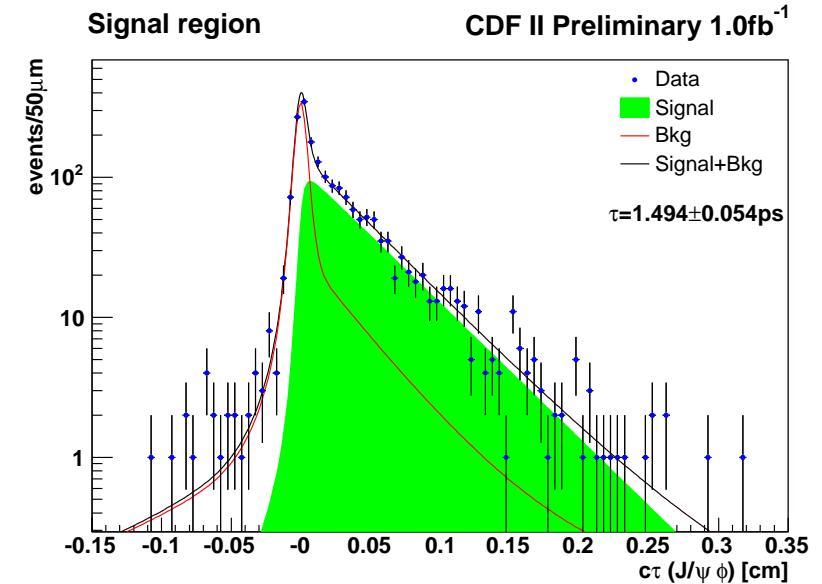
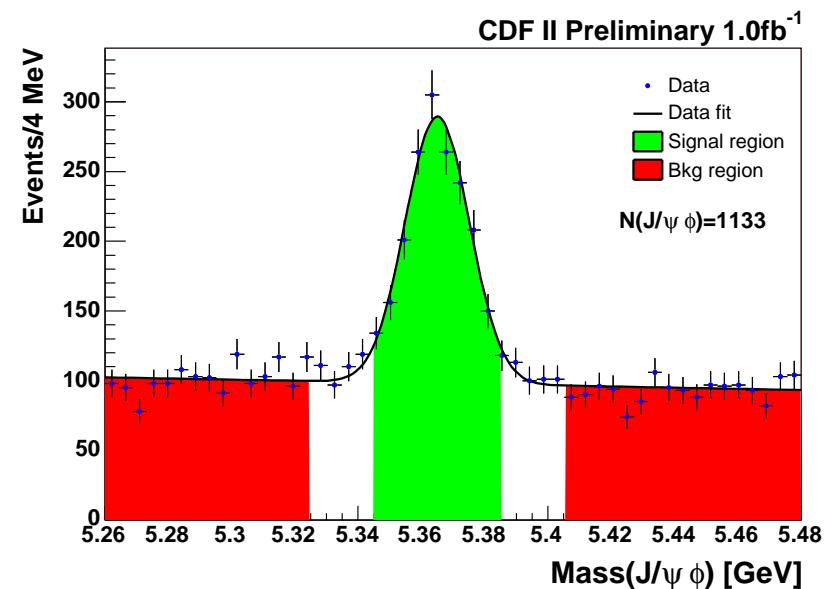


- Topology similar to $B^0 \rightarrow J/\psi K^{*0}$

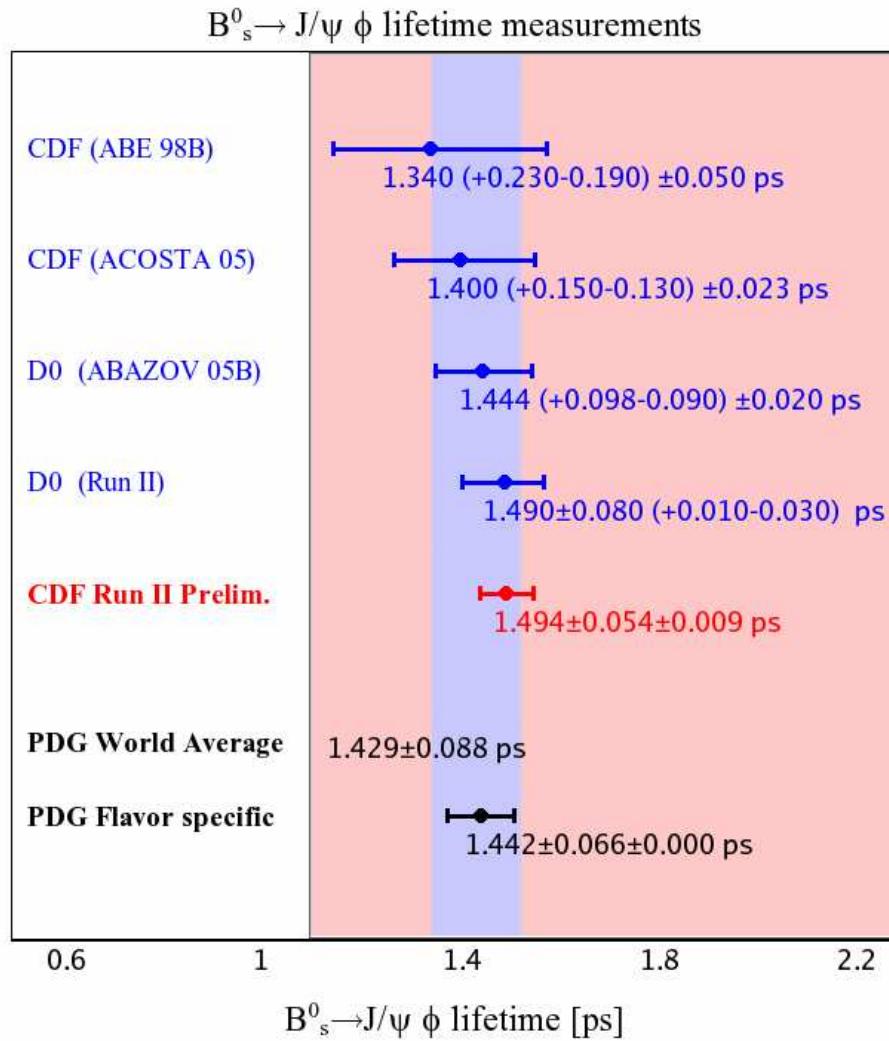
$$N(J/\psi \Lambda) = 1133$$

$$c\tau(B_s^0) = 447.9 \pm 16.2(stat) \pm 2.8(syst)\mu m$$

$$\tau(B_s^0) = 1.494 \pm 0.054(stat) \pm 0.009(syst)ps$$



Summary of B_s^0 Lifetimes



$$\frac{\tau(B_s^0)}{\tau(B^0)} = 0.963 \pm 0.047(stat) \pm 0.005(syst)$$

- Agrees well with world average
- Agrees well with theoretical prediction

$$\tau(B_s^0)/\tau(B^0) = 1.00 \pm 0.01$$

$B \rightarrow h^+h^-$ Introduction

Displaced Track Trigger used to trigger on charmless B decays

- $B_d \rightarrow K^+ \pi^-$
- $B_d \rightarrow \pi^+ \pi^-$
- $B_s^0 \rightarrow K^+ K^-$
- $B_s^0 \rightarrow K^+ \pi^-$

$B \rightarrow h^\pm h'^\mp$ fractions fit using multidimensional simultaneous unbinned likelihood fit

- Rely on dE/dx and Time-of Flight information
- Separate the modes on statistical basis

⇒ Measure both lifetime of B_d and B_s at once

⇒ Assuming the Standard model (ie $\phi \sim 0$) $\Delta\Gamma_s$ can be extracted from

$$\tau_L = \tau(B_s^0 \rightarrow K^+ K^-)$$

$$\Gamma = \frac{1}{\tau}$$

$$\Gamma \equiv \frac{1}{2}(\Gamma_H + \Gamma_L)$$

$$\Delta\Gamma \equiv \Gamma_L - \Gamma_H$$

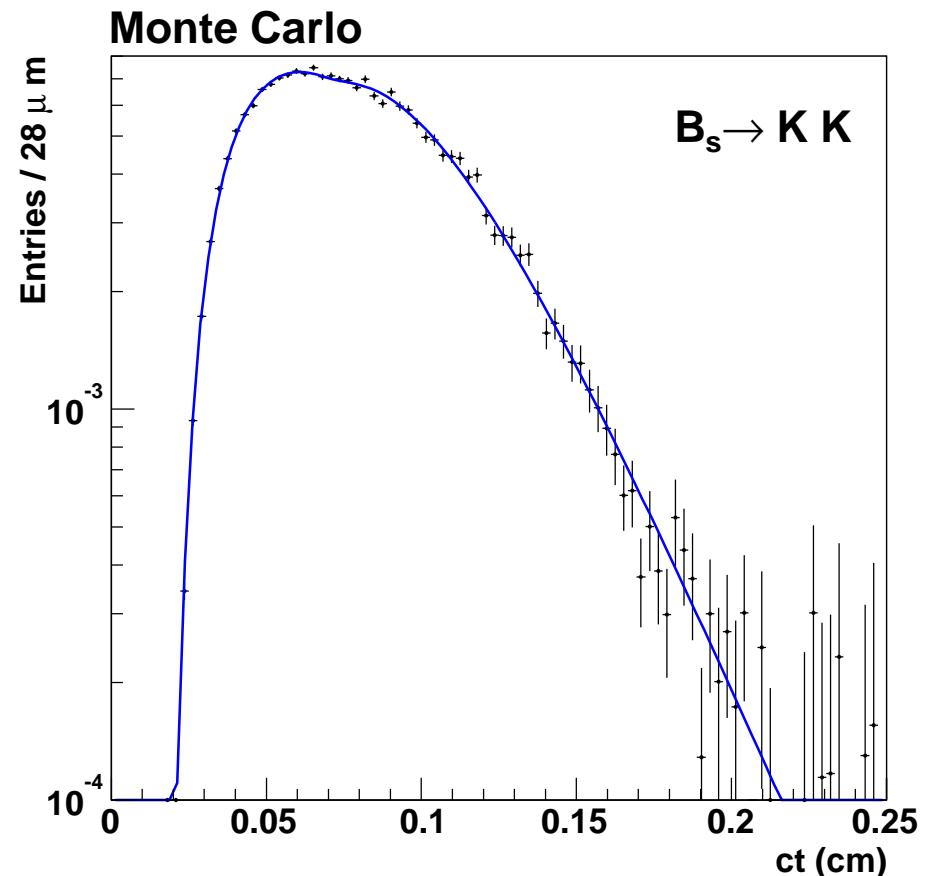
Correcting for TTT Bias

Displaced Track Trigger introduces lifetime bias
Monte Carlo based method used to correct for trigger bias

- Efficiency function describes trigger bias in terms of measured quantities.

$$\epsilon(ct) = \frac{Histo^{TTT}(ct)}{\sum_i \exp(ct, c\tau^{MC}) \otimes \text{Gauss}(\sigma_{ct}^i)}$$

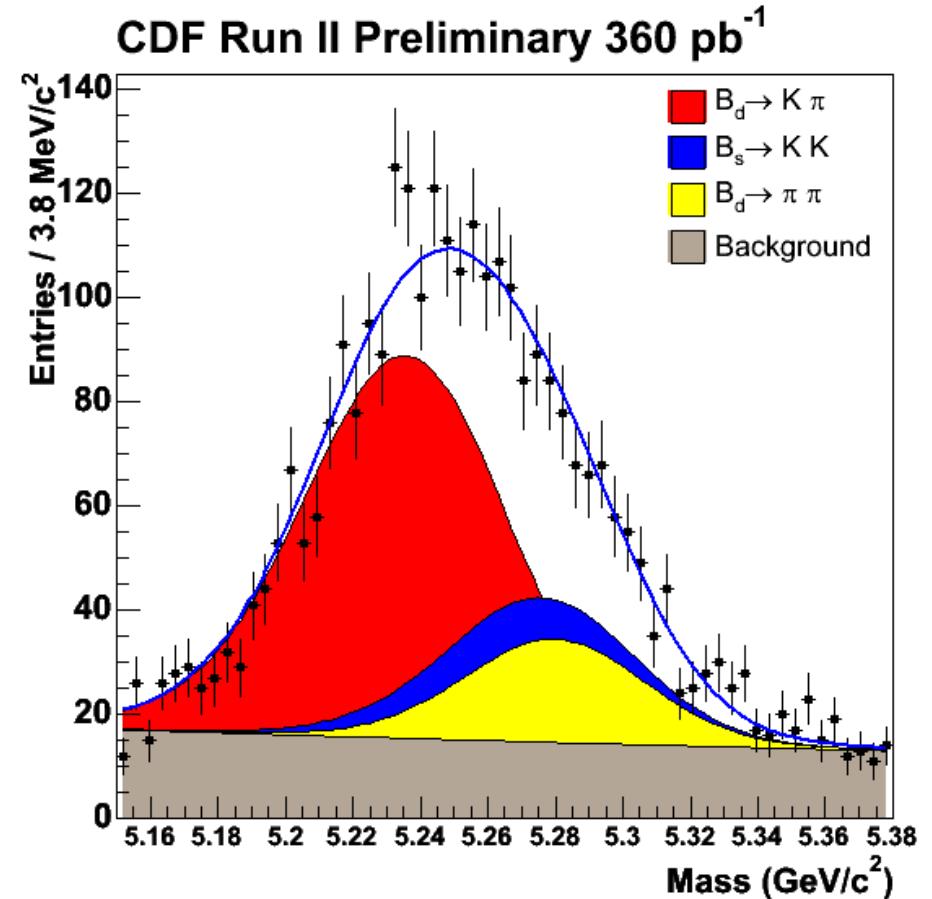
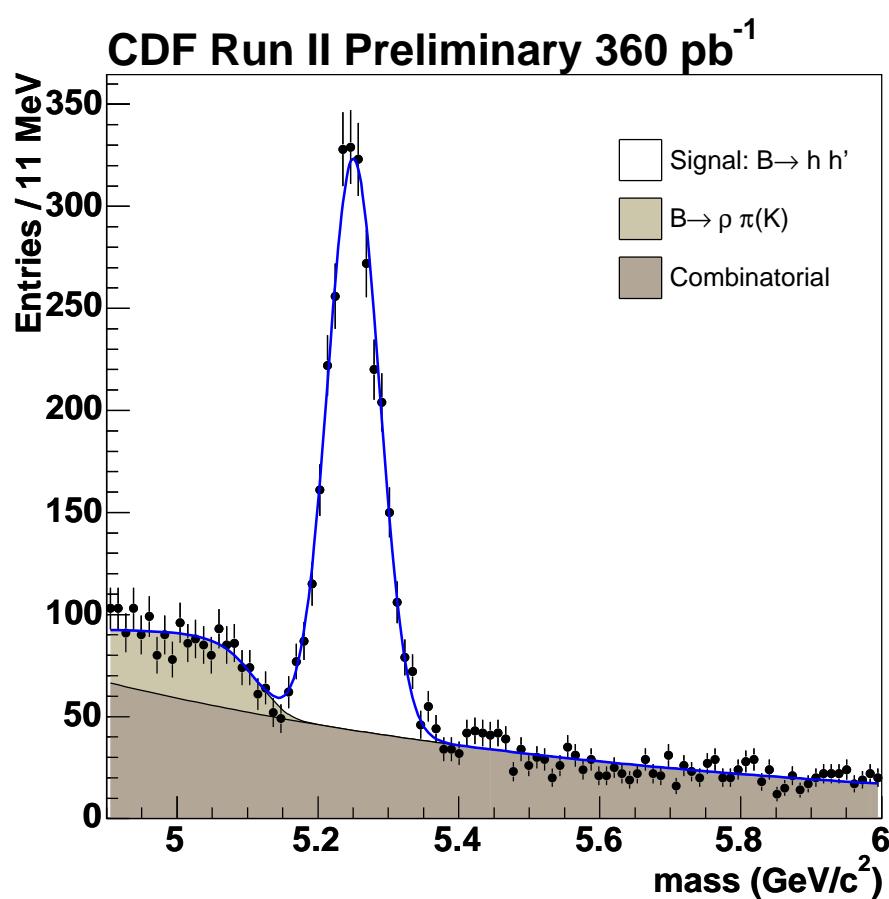
- ⇒ Numerator: histogram of events passing cuts
⇒ Denominator: Sum over events passing cuts convoluted with Gaussian resolution function



Lifetime PDF multiplied by $\epsilon(ct)$ to correct trigger bias

$B \rightarrow h^+ h'^-$

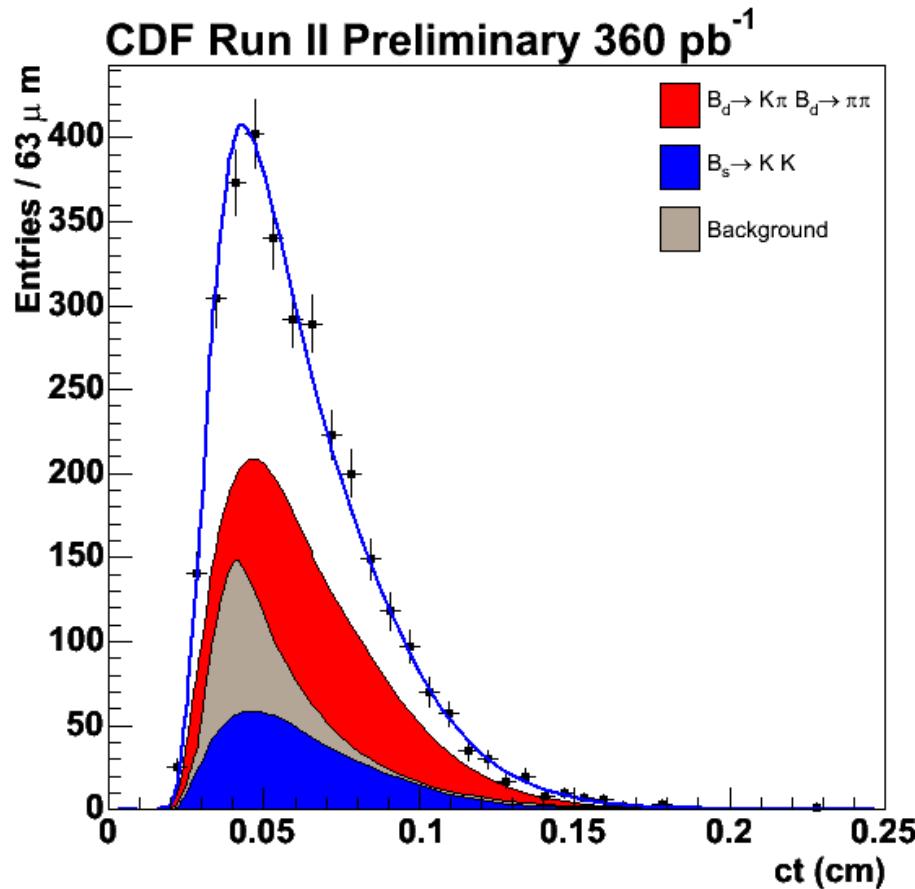
(Analysis done on 360pb^{-1})



- Events in signal region fit with multidimensional unbinned maximum likelihood fit
 - Templates derived from Monte Carlo

$B_s^0 \rightarrow K^+K^-$ Lifetime

First measurement of $\tau(B_s^0)$ and $\tau(B_d)$ in 2-body charmless decays



$$c\tau(B_d) = 452 \pm 24(stat) \pm 6(syst) \mu m$$

$$c\tau_L = c\tau(B_s^0 \rightarrow K^+K^-)$$

$$c\tau_L(B_s^0) = 458 \pm 53(stat) \pm 6(syst) \mu m$$

Using World Ave.

$$\tau(B_s^0) = 1/\Gamma_s = 438 \pm 17 \mu m$$

$$\Rightarrow \Delta\Gamma_s/\Gamma_s = -0.09 \pm 0.23(stat) \pm 0.03(syst)$$

Outlook and Conclusion

- CDF and Tevatron are working extremely well
- Many interesting lifetime measurements have been made
- B^0, B^+ lifetime results agree well with world average and theoretical predictions
- World's best Λ_b^0 lifetime measurement
- Λ_b^0 result is higher ($\sim 3\sigma$) than world average and theoretical predictions
- World's best B_s^0 lifetime measurement
- B_s^0 results agree well with world average and theory
- First lifetime measurements in B^0 and B_s^0 two-body charmless decays